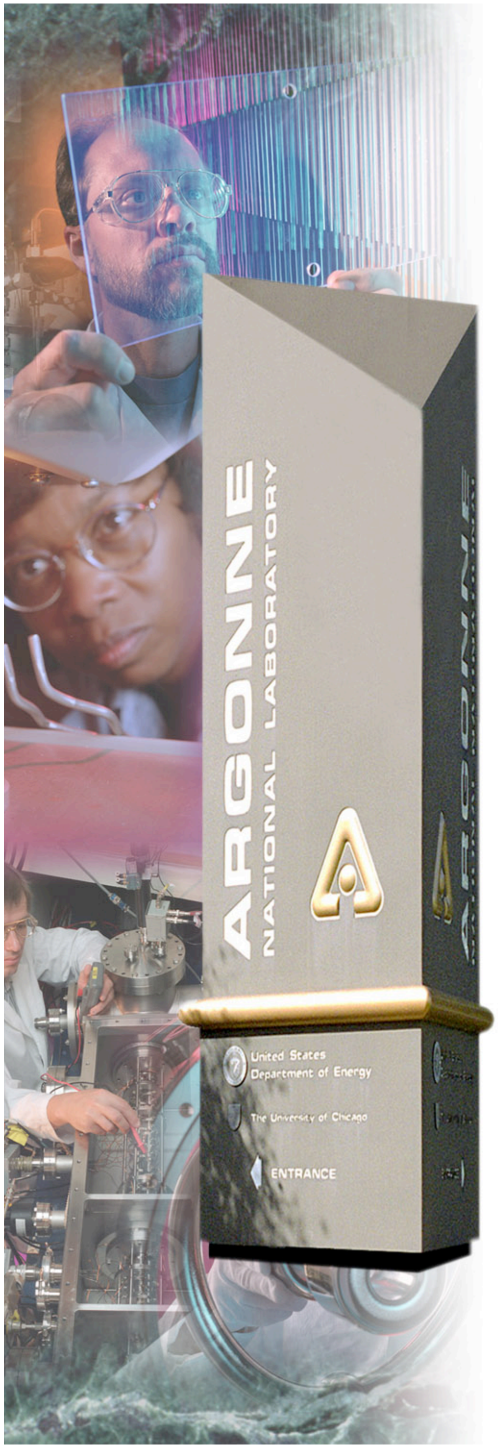

NSTX: SOL and Divertor Plate During ELMs

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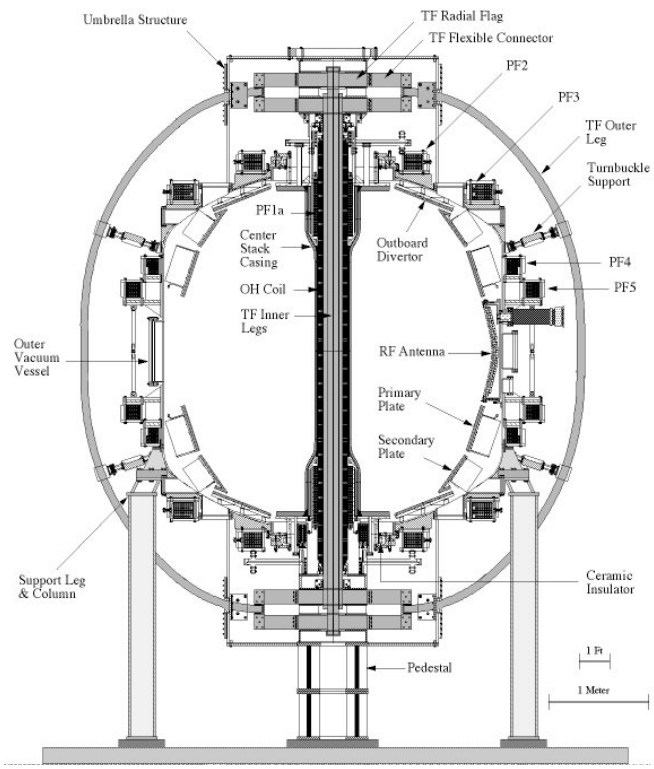
I. Introduction



R = 85.4 cm, a≤ 67 cm, Vo=12 m^3 , elongation: k=2.0
triangularity: δ=0.2, I_p=1.5 MA,
B_θ(r=0) = 0.45 T, B_θ (r=a) = 0.25 T, B_φ(a) = 0.2 T,

τ_E=50 ms , n_e=$5\cdot10^{19}$ m^{-3} ,
T_i(r=0)=2.0 keV, T_e(r=0)=1.5 keV,
$T_{pedestal}$ = 250 eV, Z_{eff}=2-3

Divertor –Carbon, T_{s0}=500 K , τ_{ELM}=0.5 ms, deposition d_{ELM}=1.5 cm
Expansion of SOL - η=$d_{divertor}$/d_{ELM} =5,
Parallel length from X-point to target is L_X=4 m.
The typical X-point height H_x=20 cm.

Energy/Particles Transport During Elms
- Knowledge Up To Date

- **Filamentary structures correlated with ELMs in NSTX plasmas. The filamentary structures had a spiral pattern. Strong and numerous filamentations were observed with giant ELMs, whereas grassy ELMs occurred with weak filamentations.**

- **Both theory and experiment from many devices suggest that convective "blob" transport in the SOL with radial velocity $V_{blob} \approx 10^5$ cm/s can compete with and/or dominate diffusion.**

Energy/Particles Transport During ELMs - Knowledge Up To Date

- "Blobs" are cross-section of filaments.
- Based on measurements, ELMs can be distinguished by the number and strength of filamentations.
- Up to 5 observed ELMs types carry energy up to (5-15) % of tokamak plasma energy:
  - **Large, Type I ELMs** with stored energy drop between (5-15),
  - **"Medium" Type II/III and small ELMs** with stored energy drop between 2-3 %.

Energy Losses During ELMs

- Core energy drops during giant ELMs by up to 30%. As pedestal energy is about 30% of total - that could mean that most pedestal energy were expelled out.

- It is better to use the term “ELM’s magnitude”:

$0 < \xi < 1$, as fraction of lost pedestal energy.

Energy And Particles Deposit From Core Plasma Into The SOL

- **Energy and particles deposit are:**

$$Q_{ELM} = \xi Q_{pedestal}, \quad Q_{pedestal} = 0.3 \cdot Q_{tokamak}, \quad N_{ELM} = \xi N_{pedestal}$$

- **Assumption**:

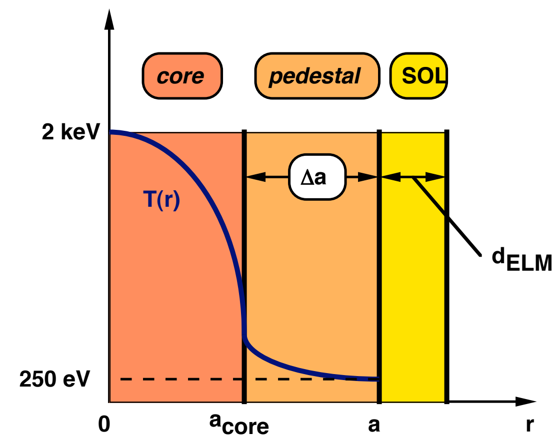
$$n_{pedestal} = n_{core}, \; Z_{pedestal} = Z_{core} = 2\text{-}2.5, \quad \zeta = (1+Z)/2 = 1.5$$

- **Energy densities, volumes and sizes are:**

$$q_{core} = 7.2 \cdot 10^{-2}, \quad q_{pedestal} = 9 \cdot 10^{-3}, \quad J/cm^3$$

$$V_{pedestal} = 0.8 \cdot V_0, \quad V_{core} = 0.2 \cdot V_0, \quad V_0 = 12 \; m^3$$

$$a_{core} = 30.3 \;\; cm, \quad \Delta a = a - a_{core} = 37.6 \;\; cm$$



a_{core}=30 cm
a=67.8 cm
d_{ELM}=1.5 cm

Energy And Particles Deposit From Core Plasma Into The SOL

$$Q_{heat} = 300,\ Q_0 = 245,\ \ Q_{core} \approx 171,\ \ Q_{pedestal} \approx 74,\ \ Q_{rad} = 55\ kJ.$$

$$W_{rad} = 1.1\ \ MW,\ \ W_{loss} = 4.9\ \ MW,\ \ \ W_{NB} = W_{rad} + W_{loss} = 6\ \ MW$$

$$N_{core} \approx 1.2 \cdot 10^{20},\ N_{pedestal} \approx 4.1 \cdot 10^{20},\ N_{tokamak} = N_{core} + N_{pedestal} \approx 5.3 \cdot 10^{20}$$

- **Concentration of Carbon impurity, $\xi_{carbon} \approx 0.3$ (from average charge Z=2-2.5)**

- **Energy and particles deposited to the SOL during ELM are**

$$Q_{ELM} = \xi Q_{pedestal} = 74 \cdot 10^4 \xi,\quad J$$

$$N_{ELM} = \xi N_{pedestal} = 4.1 \cdot 10^{20} \xi,\quad ion$$

II. SOL During ELM

- **Average density, n_{ELM}, on the midplane is determined from condition of quasistationarity**

$$\frac{N_{ELM}}{S_{out} \cdot \tau_{ELM} \cdot d_{ELM}} = \frac{n_{ELM}}{\tau_{II}}, \qquad \tau_{II} = \frac{L_{II}}{V_{II}},$$

$$L_{II} = \lambda_x L_{connect}, \; L_{connect} = 4.8 - 9.6\, m, \; \lambda_x \approx 1$$

- **S_{out} is the area of tokamak plasma surface**

- **For $\xi_{carbon} \approx 0.3$ mass velocity, $V_{II} \approx 100$ km/s**

- **From $S_{out} = 56\ m^2$ density is**

$$n_{ELM} = \frac{N_{ELM} \cdot \tau_{II}}{S_{out} \cdot \tau_{ELM} \cdot d_{ELM}} \approx 3 \cdot 10^{13} \frac{\lambda_x \xi}{\zeta}, \; cm^{-3}$$

Divertor Plate Temperature

- The target surface temperature, T_s, is determined by heat deposited onto the divertor plate surface, i.e., energy load q_{ELM} per cm^2 per ELM event.

- Average temperature jump, ΔT_s, depends on magnitude of ELMs, 0< ξ <1, and expansion ratio, η:

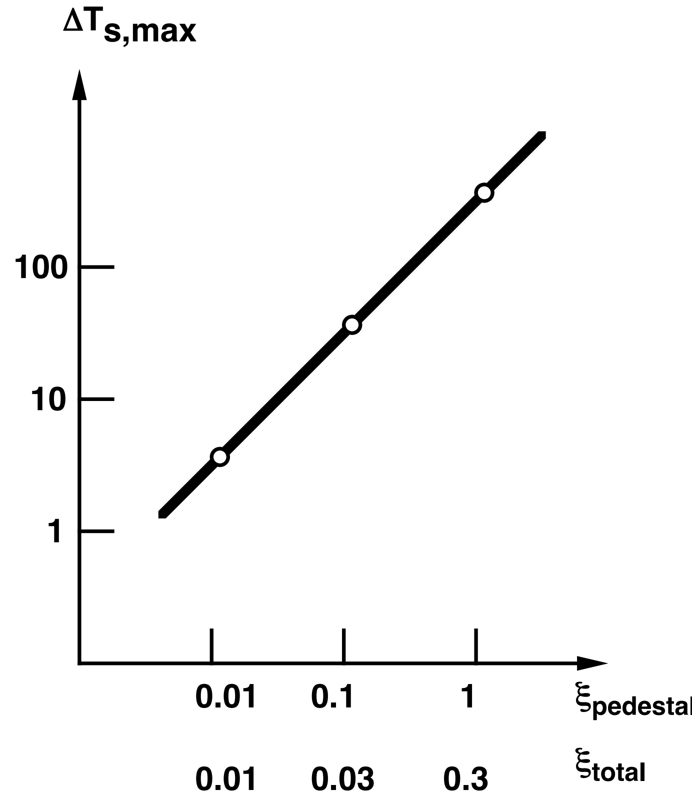
$$\Delta T_s = \frac{q_{ELM,plate}}{c_p h_{dif}} \approx 914.4 \cdot \frac{\xi}{\eta}, \quad K$$

$$h_{dif} = \sqrt{2\chi\tau_{ELM}} \approx 2.2 \cdot 10^{-2} cm$$

- **Averaged, T_s, ΔT_s, and Maximum, $T_{s,max}$, $\Delta T_{s,max}$, plate temperature and temperature jumps, in dependence on ELM magnitude**

- **For Gaussian distribution of energy/particles deposition the maximum temperature, T_{max}, can be calculated as:**

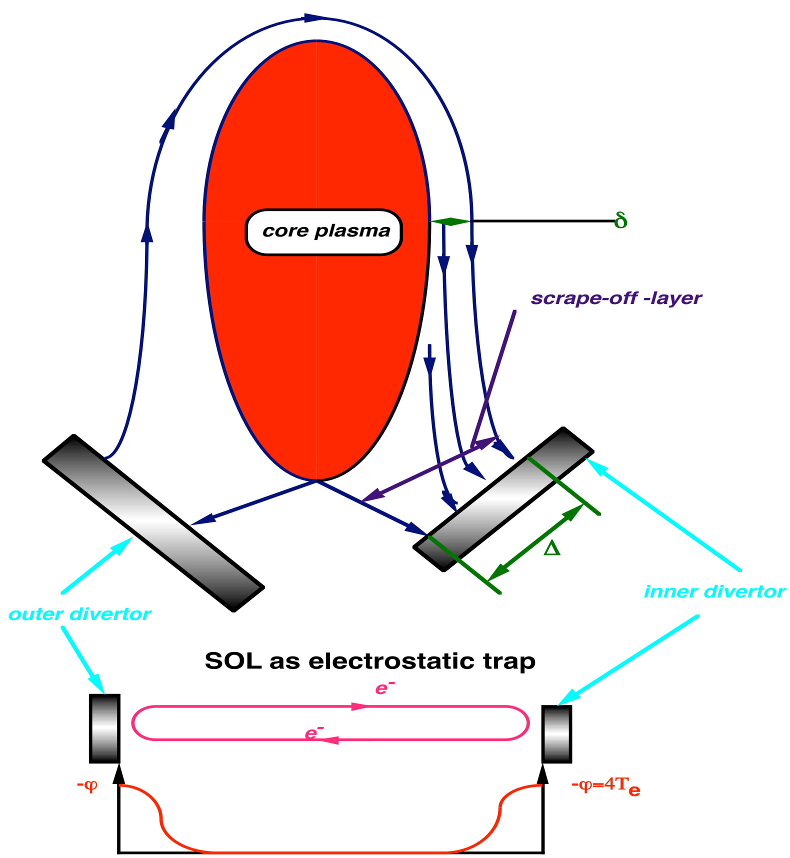
ξ	ΔT_S	T_S	ΔT_{max}	$T_{s,max}$
1%	2	502	3.5	503.5
10%	20	520	35	535
100%	200	700	350	850

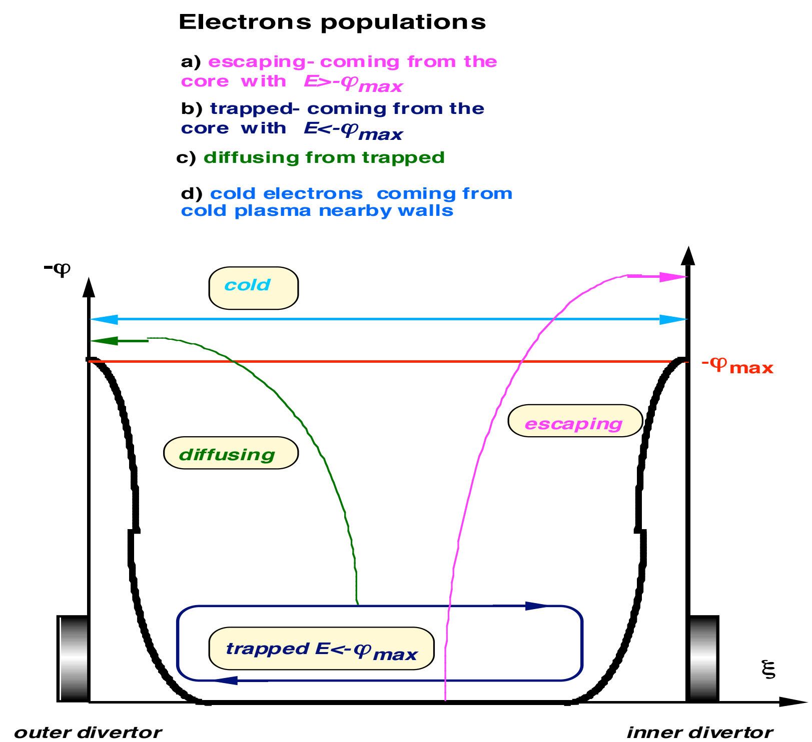


III. Erosion Of Divertor Plate

- Temperature of divertor plate is determined only by total energy deposited and has a maximum value around 850K.
- However, erosion rate depends on the form of energy reaching divertor plate surface. Particles (Deuterium- 70%, Carbon- 30%, and electrons) coming into SOL from tokamak with equal energy (temperature).
- Further energy redistribution takes place: between ions and between ions and electrons.
- Plasma in NSTX SOL during ELMs is collisionless and different than that of the collisional SOL behavior during normal operation.
- "Collisionless" does not mean collisions is neglected because large part electrons oscillating between divertor plates located at distances much shorter than particle path length (collisionless in space) will have lifetimes determined by collisions (collisional in time).

SOL Structure during ELMs





Energy Redistribution

- Redistribution of energy takes place from electrons to ions which is accelerated by electric potential between the SOL plasma and plate: ions gain energy, electrons cools down.

- *In the absence of diffusion across magnetic field* dynamics of ions and electrons can be regarded along separate magnetic field lines.

- From energy balance

$$E_{i0}^{II} + E_{i0}^{\perp} + E_{e0} = E_{i}^{II} + E_{i0}^{\perp} + \frac{3}{2}T_{e},$$

$$E_{i}^{II} = E_{i0}^{II} + |e\varphi|, \quad \frac{e\varphi}{kT_{e}} = \ln\sqrt{m_{i}/m_{e}} \approx 5$$

$$T_{e} = \frac{3}{13}T_{e0} \approx 60\ eV, \quad E_{i}^{II} = \frac{43}{26}T_{0} \approx 410\ eV$$

- **Actually energy of electrons almost (80%) transfers into ions energy through its acceleration by electric potential jump nearby the wall.**

- **Ions accelerated to energy ≈ 2 times more than its initial thermal energy along magnetic field lines.**

- **It changes slightly angle of ion impact with plate, θ_{impact}.**

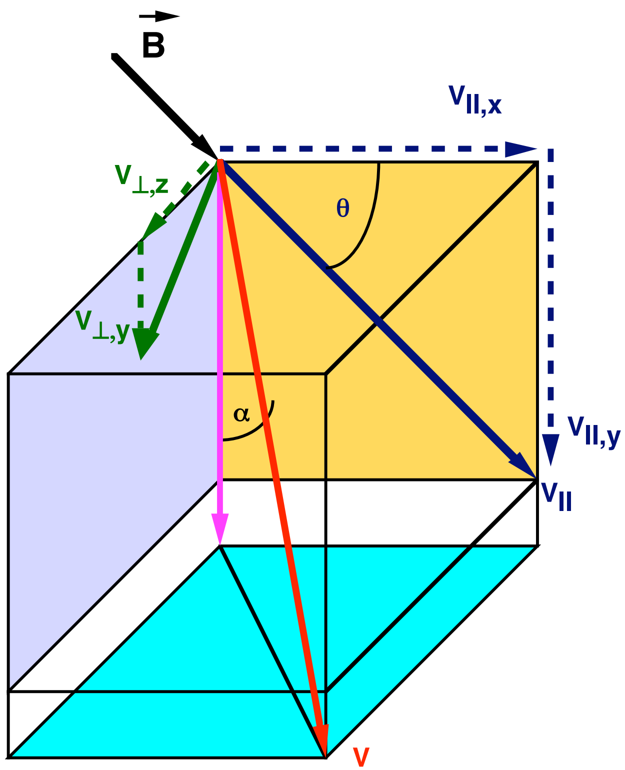
$$\theta_{impact} = 7.9° < \theta = 10°$$

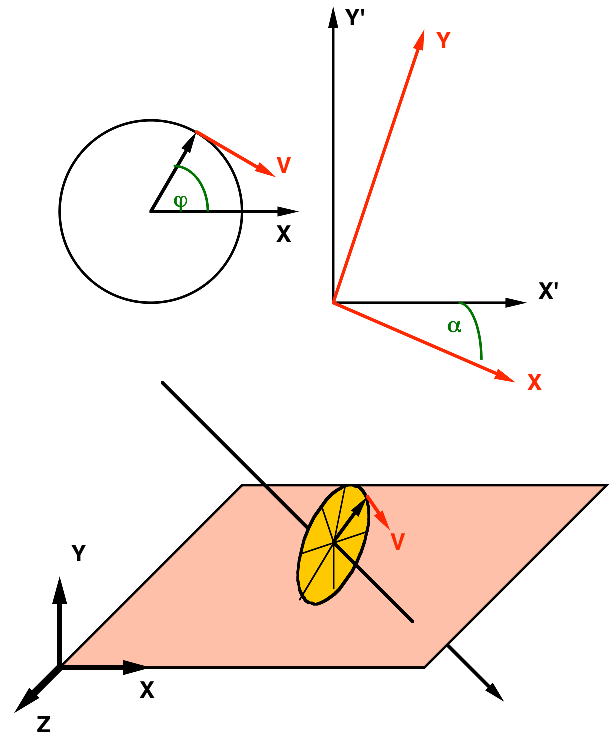
- **The averaged impact angle, α ≈ 1 radian**
- **Because magnetic filed inclination angle is relatively large, $\theta \approx 10°$, the second double electric layer is absent in comparison to small aspect ratio tokamaks like ITER.**

Interaction Angle

- **The averaged impact angle, α, determined as angle between particle velocity and normal to the divertor plate surface is**

$$<\cos\alpha> = u_{II}\sin\theta + \tfrac{2}{\pi}u_{\perp}\cos\theta,\quad u_{II} = \frac{V_{II}}{|V|},\quad u_{\perp} = \frac{V_{\perp}}{|V|}$$





Interaction Angle

- **With acceptable accuracy for this case, the average angle of impact can be estimated as**

$$\bar{\alpha} \approx \arccos\left(u_{\perp}\right) = 52° \approx 1 \quad radian$$

$$|V| = \sqrt{V_{\perp}^{2} + V_{II}^{2}}, \quad V_{\perp} = \sqrt{\frac{T_0}{m_i}}, \qquad V_{II} = \sqrt{\frac{43}{26}\frac{T_0}{m_i}},$$

$$u_{\perp} = \frac{\sqrt{T_0/m_i}}{\sqrt{T_0/m_i + \frac{43}{26}T_0/m_i}} = \sqrt{\frac{26}{69}} \approx 0.614$$

Sputtering

- Sputtering is produced by deuterium ions and carbon ions with energy:

$$E_i = \frac{69}{26} T_0 \approx 660 \ eV, \quad T_0 = 250 \ eV$$

- Electron gas cools from $T_0 = 250$ eV to $T_e \approx 60$ eV.

- It would be very helpful to measure electron temperature in the SOL during ELMs.

Sputtering Yield

- **Total number of ions coming onto surface is**

$$N_{depo} = \frac{N_{ELM} \cdot \xi}{S_{out} \cdot d_{ELM} \cdot \eta} \approx 0.8 \cdot 10^{13} \xi, \quad \frac{1}{cm^2 \cdot event}$$

that corresponds to sputtered carbon atoms/ions number

$$N_{sput} = \psi N_{depo}$$

where ψ (atoms/ion) is the erosion yield due to sputtering, .

Because of the **interaction between deuterium and carbon ions the average energies of both species are assumed equal.**

Erosion

- Number of physical sputtered particles per cm² is

$$N_{phys} = N_{sputD} + N_{sputC} = \left(0.7\psi_{DC} + 0.3\psi_{CC}\right) N_{depo}$$

$$N_{sputD} = 2.4 \cdot 10^{11}\xi, \quad N_{sputC} = 2.8 \cdot 10^{11}\xi, \quad N_{phys} = 5.2 \cdot 10^{11}\xi, \quad cm^{-2}$$

- Number of chemically sputtered particles per cm² is

$$N_{chem} = \psi_{chem} N_{depoD}, \qquad 2 \cdot 10^{-2} < \psi_{chem} < 5 \cdot 10^{-2},$$

$$N_{chem} = (1.2 - 2.8) \cdot 10^{11}\xi, \qquad cm^{-2}$$

Total number of sputtered particles per cm² is

$$N_{sput} = N_{phys} + N_{chem} = (6.4 - 8) \cdot 10^{11}\xi, \qquad \# / cm^2 / ELM$$

- **Vapor flux, F_{vapor}, at T<1000 K is very small and can be neglected**

IV. Summary

1. Concentrations of D and C is determined by average Z =2-3 , thus ion flux reaching divertor plate consists of 70% deuterium and 30% carbon. Contribution of carbon ions sputtering is comparable with sputtering by deuterium ions.

2. During ELM's the SOL plasma is collisionless.

3. Ions accelerates in region nearby target surface to energy of ≈ 2 times of its initial:

$$E_i \approx 2\ E_{i0} \approx 660\text{eV}.$$

IV. Summary

4. **In the SOL energy transfers from electrons to ions thus electrons cools down to $T_e \approx 0.2T_{e0} \approx 60$eV.**

5. **Divertor plate surface temperature is determined by**

   a) Magnitude of ELMs, ξ,

   b) SOL expansion from midplane toward divertor plate, η,

   c) Size of deposition at midplane , d_{ELM}.

6. **At $\xi=1$ (Giant ELM) , $\eta=5$, $d_{ELM}=1.5$ cm, the surface temperature can increase up to $T_{s,max} = 850$ K.**

7. **Contribution of Carbon and Deuterium ions to total sputtering yield is comparable.**